An NACP Field Intensive to Study Atmosphere-Surface Carbon Exchange over Forested Landscapes of the Southeastern United States

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Introduction

The central objective of the NACP is to measure and understand the sources and sinks of CO_2, CH_4, and CO in North America and adjacent ocean regions. The NACP develops improved bottom-up models, based on ecosystem processes aggregated to continental scale using data sets developed in the NACP. The NACP database will also enable better top-down estimates of the carbon budget for North America.

The NACP Science Plan is divided into four program elements: 1. Long term atmospheric measurements, 2. Intensive field programs, 3. Land and ocean processes, fluxes, and carbon stocks and, 4. Integration, diagnosis, and prognosis using models, data, and model-data fusion. The intensive field programs were envisioned primarily as a way of evaluating methodological approaches and testing key hypotheses.

We assume that an intensive of some nature will be conducted over the Harvard forest site that will satisfy the objectives of the NACP for the north eastern deciduous forests. In this white paper, the GSFC Carbon Theme Team proposes an intensive in the forest biome of the south-eastern US, focused on (1) testing key hypotheses related to the impact of disturbance and recovery on carbon sources and sinks in such ecosystems and (2) testing and developing measuring and modeling concepts and data fusion techniques critical to the success of achieving the stated NACP objectives. We discuss the rationale for selection of the SE US forest biome, the requisite site characteristics and process for selection of an intensive site, but at this point, no specific location for the intensive.

Rationale

Top-down analyses of spatial and temporal variations in the atmospheric CO_2 records have suggested that carbon sinks are located at latitudes above 40^{o} N (Tans et al, 1990, Denning, et al., 1995, Ciais, et al, 1995, Bosquet et al,2000). These studies further implicate the North American land area as a major sink averaging 1 to 2 Pg C yr^{-1} or about 15 to 30% of the anthropogenic CO_2 flux from fossil fuel combustion. However, the exact location and processes by which the carbon is removed are not well understood, nor is it understood how long this rate of sequestration can be sustained in the face of climate change. Forest-cover conversion, disturbance, and recovery have been proposed as primary mechanisms for transferring carbon between the land surface and the atmosphere, but the area and timing of these processes is still poorly quantified. For the coterminous United States, Pacala et al.(2001), estimated a sink of between 0.30 - 0.58 Pg C yr^{-1} about half of which may be forest regrowth from disturbance and past land-cover clearing. These estimates of forest regrowth were based on ground samples of biomass from 1977 to 1992 from the US Forest Service. However, the authors were only able to bound this carbon flux component between 0.11 and 0.15 Pg C yr^{-1} , an uncertainty of about ±25%.

Given the importance of disturbance and recovery to quantifying biospheric carbon fluxes, it makes sense to turn attention to landscapes where disturbance processes are rapid and pervasive. The pine and mixed deciduous forests of the Southeastern United States have undergone a long-term (100 year) transition from agricultural land use, to secondary mixed forests, and finally to rapid-rotation plantation pine stands. Commercial logging operations are pervasive, and in these areas at least it is likely that harvesting and regrowth are very roughly in steady state. Statistics from the Forest Inventory and Analysis (FIA) system clearly illustrate the band of rapid-rotation forestry (dominated by loblolly, slash, and white pine cultivation) that stretches from southern Virginia to Louisiana (Fig 1), with extremely young pine forests dominating the region. In addition, there are areas of abandonment of cotton and other croplands with subsequent regrowth into forests.

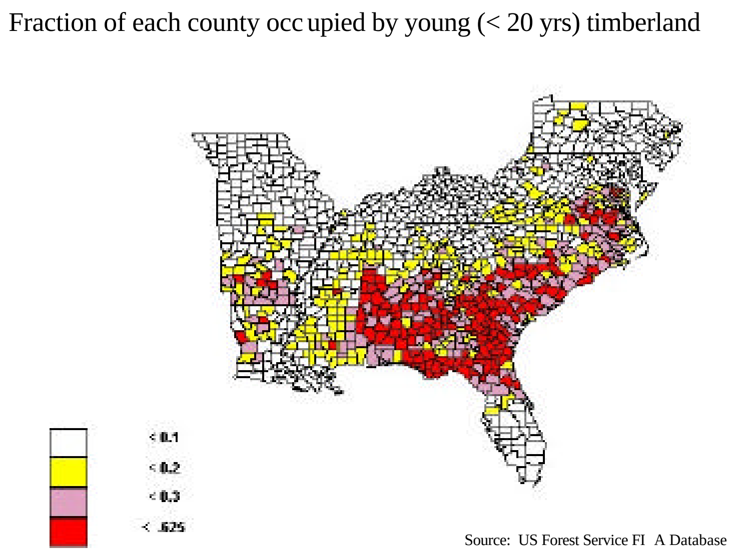

Figure 1: Fraction of each county in the SE US forests occupied by young (< 20 yrs) timberland

The implications of the disturbance and recovery dynamics in the SE forests for the North American carbon cycle are poorly understood. Existing eddy-correlation flux data from Duke Forest and Gainsville Florida suggest high annual values of net ecosystem exchange (NEE) for recently cleared pine stands, ranging from 349 to 416 $gCm^{-2}yr^{-1}$ for stands aged 10 to 17 years old (Thornton et al., 2002). These data follow the “classical” model of disturbed forest stands releasing carbon for some years following disturbance through litter and soil decomposition, followed by increased NPP and NEP during youth, finally culminating in near-equilibrium carbon exchange in later years. In large part due to the young age of these forests, Turner (1995) concluded that the southeast and south-central regions had the strongest biological carbon sinks in the nation (~80 $Tgyr^{-1}$). However, large carbon emissions due to harvest may essentially offset this sink. As a result, Birdsey and Heath (1995) argued that by 2040 the region would become a net carbon source, primarily due to decreased rotation periods and continued expansion of plantation pine into areas of high-biomass, mature mixed forest. They also noted that the soil carbon dynamics associated with rapid rotation forestry were poorly known, and in fact, assumed no net change to soil pools in their accounting.

Of particular interest (and little studied to date) is the interannual variability of southeastern forest clearing, and the long-term conversion rate of mixed deciduous forests to planted pine. Both of these factors will affect the net carbon balance for the region as well as its variability. In addition, recent increases in precipitation over the continental U.S. (Dai et al., 1997) due to changes in ocean circulation and the ocean-atmosphere teleconnections may be affecting the carbon cycle in the SE US and elsewhere. Carbon cycling model studies (Nemani et al, 2003) suggest that recent precipitation increases in concert with correspondingly lower values for vapor pressure deficit, and cooler temperatures may have increased net ecosystem production (NEP) in the SE forests.

In addition to testing these science hypotheses, an intensive in the SE forests would be ideal for testing many of the critical technical issues involved in the NACP analysis framework – tall tower measures of regional-scale CO_2 flux, bottom-up modeling of these fluxes and remote sensing of terrestrial ecosystem parameters needed as input to the analysis framework. Large regions of relatively moderate terrain can be found as well as well established research sites such as the Duke Experimental Forest and institutions such as Duke University, North Carolina State and the University of North Carolina.

Science Hypotheses Addressed by the SE US Intensive

(a) Rapid rotation forestry and recent precipitation increases represent a significant, if transient, carbon sink due to increased NEP of young forests.
(b) Afforestation following abandonment in ecosystems in the late 19^{th} and early 20^{th} centuries, is currently a sink for NA carbon.
(c) The sink strength resulting from these processes will decrease as the (i)regenerating forests near maturation and (ii) decomposition of harvest products release carbon.
(d) In the future, variations in the sink/source strength will be driven primarily by interannual climate variations, longer-term secular climate trends, increases in atmospheric CO_2 and anthropogenic activities, such as forest management policy and industrial nitrogen deposition.

Critical Technical Issues to be Evaluated

(a) How accurate do remote sensing measurements need to be, and how well must process models perform to provide "bottom-up" estimates of annual carbon accumulation or release rates to an accuracy of 0.1 petagram-yr^{-1} over a 1000 km^2 region?
(b) Can remote sensing obtain with sufficient accuracy the necessary inputs to the process models (e.g. age distribution, biomass, successional stage, biophysical characteristics)?
(c) Can the process models, accurately compute the carbon sink/source function and its dependence on climate and anthropogenic factors?
    - ? Can the above-ground biomass accumulation be modeled with sufficient accuracy as a function of climate variations and trends, increases in atmospheric CO_2, and anthropogenic activities?
    - ? Can the below-ground biomass be modeled as a function of landscape characteristics such as community composition, vegetation successional stage, soil type, topography etc?
(d) Can the process models be validated at the intensive site scales using flux data from the tall towers?

Integration, Diagnosis, and Prognosis, the NACP Analysis Framework

The NACP data analysis framework involves three coordinated analysis elements: (1) "**bottom-up**" approaches involving ecosystem process models, measurements and other techniques that elucidate the ecological, biological and physical processes involved in the surface-atmosphere exchange of carbon (2) "**top-down**" approaches that involve atmospheric transport models and composition measurements designed to locate and quantify surface sources and sinks of carbon and (3) "**data fusion**" approaches designed to integrate the understanding garnered from the bottom-up and top-down approaches into an analysis capability for addressing the NACP stated objectives.

Developing **bottom-up** approaches requires the creation and validation of new diagnostic models that are spatially explicit and constrained by greatly improved measurements of C inventories, with careful analysis of all carbon pools. Both land and ocean models will be driven by data that will be measured in the NACP. The models must produce spatially explicit, time-resolved fluxes amongst major C pools and the atmosphere, providing continental-scale carbon budgets on all time scales.

Top-down approaches derive atmosphere-surface fluxes from atmospheric measurements, with spatial information on fluxes associated with land or ocean surface properties such as vegetation type, NDVI, or pCO_2. This is the classical "inverse model" concept. NACP will provide more highly resolved data than previously available, both spatially and temporally, enabling inverse models to derive reliable continental-scale carbon budgets.

The NACP **data fusion** approach brings these two methods together in a data assimilation framework. The fluxes predicted by the bottom-up models will be used to generate atmospheric concentration gradients using assimilated wind fields. The atmospheric data can then be inverted by optimizing parameters of the bottom-up models, instead of adjusting surface fluxes themselves as in an inverse model. In the data assimilation framework, this integrated biosphere-atmosphere real-time model is optimized against **all types** of data, ranging from surface fluxes at the 100 ha scale, inference of vegetation activity from remote sensing, ocean chlorophyll, boundary layer and large-scale CO_2 gradients, etc.

The four elements of the NACP implementation plan are focused on developing and validating this analysis framework to address the NACP science questions. The intensive field programs will focus on addressing specific, challenging issues that are critical to the success of the overall NACP, that require unusual concentrations of resources, and that are time sensitive (i.e., lack of progress on this topic hinders other major elements of the program). Below, we describe such an intensive, aimed at addressing science hypotheses relevant to the NACP and the associated critical technical issues as in the introduction.

The science hypotheses to be addressed are those which ultimately must be addressed at continental scales. However, by designing an intensive that can address them at a geographic scale of ~ 25 km, many of the major elements of the continental scale analysis framework will also be addressed. The intensive we describe would focus on developing and validating the bottom-up methodologies, including direct measurements of carbon exchange by remote sensing as well as combined remote sensing and modeling approaches as required by the NACP analysis framework. However, key elements of the top-down approach and the data fusion approach would also be utilized and tested. The bottom-up approach utilizes remote sensing measurements as well as ecosystem carbon models to directly measure and model surface/atmosphere carbon, water and energy exchange. While carbon exchange is of most interest to the NACP, the complete surface mass/energy exchange budget is biologically and physically linked in such a way that one cannot be accurately characterized without a proper simultaneous consideration of all exchange processes. In this regard there are a number of challenging issues critical to the success of the overall NACP, that require an intensive for resolution.

The first is the development of an observing system simulation experiment (OSSE) that specifies how accurate remote sensing measurements and model predictions need to be to provide sufficiently accurate “bottom-up” estimates of annual carbon accumulation. Such an error budget constrains both remote sensing algorithm and model development and provides experiment design and accuracy targets for validation. One focus of the intensive is to develop and validate a “bottom-up” OSSE.

A second critical issue is whether remote sensing can measure with sufficient accuracy the spatial distributions of patch age, biomass, successional stages etc, necessary to quantify long-term exchange of carbon with the atmosphere. Thus a second focus of the intensive is to quantify the accuracy of the remote sensing estimates.

Thirdly, the process models involved in the “bottom-up” computation of the carbon sink/source strengths have not been adequately validated. It is not known whether the above-ground biomass accumulation can be adequately modeled as a function of climate variation and trend, anthropogenic impacts etc. Or whether the below-ground accumulation in soils can be modeled as a function of landscape characteristics such as community composition, vegetation successional stage, soil type, topography etc. A third focus of the intensive then is to acquire sufficient insitu data and conduct model comparisons and intercomparisons to quantify model performance.

Intensive Experiment Design

The broad goals of the intensives have been discussed above. The specific objectives of the intensive are:

(1) The simultaneous acquisition of satellite, aircraft, atmospheric and surface data
  - (i) Satellite data: Terra and Aqua MODIS & MISR data, Landsat, SPOT, GOES.
  - (ii) Airborne Radiometric Data: A range of airborne remote sensing instruments would be flown during satellite overpasses, including lidar, radar and hyperspectral sensors. As an example, long wavelength VHF (20-120MHz) radar may provide useful measures of standing biomass and has the potential for providing information about rooting depth. Combined with a lidar sensor the potential exists to characterize both the total volume of plant material as well as its distribution in three dimensions (i.e., structure). The BioSAR sensor (80-108 MHz) and the airborne profiling lidar (PALS) are both currently available and have been tested together using light aircraft to collect data over forests in the eastern US as part of a NASA/DOE project on carbon sequestration. To date, no work has been carried out exploring the potential of BioSAR to address rooting depth.
  - (iii) Surface/Near-surface fluxes: measurements of CO_2, latent (evapotranspiration) and sensible heat and momentum fluxes at and above the surface.
  - (iv) Surface/Near-surface states: Measurements of atmospheric optical and meteorological conditions, surface optical, microwave, thermal, biophysical and structural properties.

(2) To obtain a rigorous understanding of the disturbance/recovery and climate processes controlling energy/mass exchange at the surface and how these are manifested in satellite-resolution data. To achieve this objective, data need to acquired over a range of spatial scales to test various methods of integrating small-scale processes (e.g. photosynthesis, transpiration, light scattering etc.) up to the scale of satellite pixels of various resolutions.

Intensive Site Characteristics

The intensive site (IT) is envisioned to be roughly 25x25 km, large enough to test the upscaling methodology, but small enough to be logistically feasible. The IT landscape should be reasonably representative of SE pine forests and contain a “tall tower” for characterizing mass and energy flux over the IT using eddy correlation methods. The IT should be situated so that urban influences to atmospheric CO_2 flux are minimal or at least can be accounted for, but also be within reasonable commuting distance of laboratory facilities and staff capable of supporting field measurements, for example a university. The site should have a history of field studies Site selection should also consider ease of access to the airspace above the site (for example not located in the approach to a major airport).

Current plans for the NACP call for the placement of tall flux towers at Grifton NC (which also operated prior to 1999), Columbia SC, and Selma Alabama. Assuming a ~100km scale fetch, all of these towers would sample significant amounts of planted pine. Initial analysis suggests that the Selma site might be preferred, since (a) the population density in the surrounding area is relatively low; (b) prevailing southern and southwesterly winds would imply a consistent fetch over intensively logged areas to the south of Selma, and (c) agriculture is less prevalent within the tower fetch compared to the other sites.

In addition to the tall tower site, which would integrate carbon fluxes on a regional basis, it would make sense to set up smaller towers, perhaps on a rotating basis, to sample NEE in various plots of known age, management history, forest type, and soil type. These data would provide a counterpart to existing Ameriflux efforts in Gainsville FL and Duke Forest, NC, and would allow a more complete understanding of how key variables affect NEE during stand evolution. As a control, flux observations should also be obtained in nearby mature mixed deciduous forests, which have undergone minimal anthropogenic disturbance in the last ~50-100 years.

Local NEE measurements from 'short' towers would provide calibration for biogeochemical models to predict NEP as a function of stand age, climate, management regime, and site condition. Given regional disturbance history (derived from Landsat observations, air photos, and/or FIA data), model predictions of biomass accumulation could be validated against FIA plot data supplemented with airborne lidar stand height data (e.g. from LVIS). The overall objective is to have a complete "bottom up" assessment of net ecosystem exchange for the entire 25x25 km site, which could then be validated against "top down" measurements of atmospheric CO_2 divergence from aircraft sampling. An additional issue to be addressed is the role of eddy-correlation aircraft in the validation of tall-tower measurements of regional CO_2 flux.

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